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AVERAGE AND LOCAL HEAT TRANSFER FOR CROSSFLOW THROUGH A TUBE BANK

R. A. DeBortoli.
Engineer

R. E. Grimble
Senior Engineer

and

J. E. Zerbe, Associate Member ASME
Supervising Engineer
Westinghouse Electric Corporation
Atomic Power Division
Pittsburgh, Pennsylvania

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ABSTRACT

Heat-transfer coefficients have been determined for a crossflow tube bank by the use of heat-and mass-transfer techniques for the Reynolds-number range of 35,000 to 80,000. The average heat-transfer coefficients agree favorably with extrapolations of existing data. The local coefficient variations from the average were as great as +80 per cent and -55 per cent.

AVERAGE AND LOCAL HEAT TRANSFER FOR CROSSFLOW THROUGH A TUBE BANK

By R.A. DeBortoli, R.E. Grimble, and J.E. Zerbe

NOMENCLATURE

The following nomenclature is used in the paper:

Roman Letter Symbols C_c = specific heat capacity of test-rod material C_p = specific-heat capacity of coolant D = diameter of test rod h = convection heat-transfer coefficient h_r = radiation heat-transfer coefficient h_t = total heat-transfer coefficient K = molar mass-transfer coefficient of naphthalene k_a = thermal conductivity of coolant k_d = molar mass-diffusion coefficient of naphthalene L = effective length of test rod M_a = molecular weight of air M_n = molecular weight of naphthalene P = total static pressure p = vapor pressure of naphthalene q'_r = flux of radiant energy T = absolute temperature of rod T_a = absolute temperature of air t = time v = maximum velocity of air

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w_c = mass of test rod

y = depth of surface removal from naphthalene rod

Greek Letter Symbols

ϵ = emissivity of rod surface for radiation

θ = total time for testing

μ = dynamic viscosity of air

ρ_a = density of air

ρ_n = density of naphthalene

σ' = Stefan Boltzmann constant for radiation

Dimensionless Parameters

j_h = heat transfer factor $\frac{h}{c_p \rho_a v} \left(\frac{c_p \mu}{k_a} \right)^{2/3}$

j_m = mass transfer factor $\frac{kp}{\rho_a v / M_a} \left(\frac{\mu}{\rho_a k_d} \right)^{2/3}$

Nu = Nusselt number $\frac{hD}{k_a}$

Pr = Prandtl number $\frac{c_p \mu}{k_a}$

Re = Reynolds number $\frac{\rho_a Dv}{\mu}$

INTRODUCTION

Heat-transfer data for crossflow through tube banks are abundantly reported in the literature for the lower Reynolds numbers. A range of Prandtl numbers and a variety of geometric arrays have been covered, and correlations have been reported. There is, for example, the Colburn equation (1), ¹ ✓

$$Nu = 0.33 (Pr)^{1/3} (Re)^{0.6}$$

¹ Underlined numbers in parentheses refer to the Bibliography at the end of the paper.

that is based on data taken in the interval from $Re = 2000$ to $Re = 32,000$. Available data become more sparse as higher Reynolds numbers are considered. The paper by Sheehan, et al. (2), who used water as a coolant at a temperature of 360 F, reports the only data known by the authors to have been taken in the range of Reynolds numbers from 10^5 to 10^6 .

It was felt that additional data for the high and intermediate Reynolds numbers would be of value. The range covered in the work reported here is between $Re = 35,000$ and $Re = 80,000$. Air was used as the flow medium and the Prandtl was taken as 0.697. The geometry was that of a bank of staggered rods so spaced that the centers of any three mutually adjacent rods lay at the vertices of an equilateral triangle the length of whose sides was 1.30 times the rod diameter.

AVERAGE HEAT-TRANSFER COEFFICIENTS

Basis of the Method of Test

The transient technique, reported by Kays, et al. (3) was used in the average heat-transfer measurements reported here. With this method, if one rod in a bank of rods is preheated and is then cooled by air flow, its temperature changes according to the equation

$$\frac{d(T - T_a)}{dt} = - \frac{h_t \pi D L}{W_c C_c} (T - T_a)$$

Here it is assumed that h_t and T_a are constant in time and that the rod is uniform in temperature. For convenience in computation, this equation may be written

$$\frac{d}{dt} \ln(T' - T'_a) = - \frac{h_t \pi DL}{W_c C_c} \dots \dots \dots (1)$$

where $T' - T'_a$ is any quantity proportional to temperature difference $T - T_a$ (for example, a thermocouple potential). Thus, a plot of $\ln(T' - T'_a)$ against t will result in a straight line of slope

$$-\frac{h_t \pi DL}{W_c C_c}$$

Apparatus and Test Procedure

The basic model for the tests is shown in Fig. 1. It consisted of nine rows of plexiglass rods, 1 in. diam. The rods were staggered so as to form an equilateral triangular array. The transverse pitch was 1.30 in. and the longitudinal pitch was 1.125 in. The rods were held in a rectangular plexiglass channel section. The inside cross-sectional dimensions were 5 5/8 in. on the side parallel to the rod axis and 6 3/8 in. on the

side normal to the rod axis. Each odd-numbered row contained five rods, and each of the even-numbered rows had four whole rods and a partial rod at either end. Any one of the three rods at the centers of rows 3, 5, and 7, counting in the direction of flow, could be removed through the sides of the channel section and replaced by an instrumented, preheated copper rod that served as a thermal capacitor.

Two different copper test rods were used. One consisted of a 0.510-lb cylinder, 4 5/8 in. in length, 1.00 in. OD, and 3/4 in. ID. The second capacitor weighed 0.864 lb and had the same dimensions as the first, except that the inside diameter was 1/2 in. A drawing of this rod is shown in Fig. 2. In order to eliminate wall effects, the copper tests rods were 1 in. shorter than the dummy rods so as not to span the entire distance between the walls of the test section. Extra length for support and preservation of flow conditions was effected by mounting the rods between Teflon end pieces of the same outside diameter. Thermal contact between the copper and the Teflon was kept to a minimum by recessing grooves in the Teflon.

A rapid-response thermocouple junction was made by drilling two small holes, close together, through the wall of the cylinder and soldering an iron wire in one hole and a constantan wire in the other. The cold junction was placed in the air stream so that the output potential of the thermocouple indicated the difference in temperature between the rod and the air. The thermocouple leads were connected to each of the sixteen pairs of terminals of a Leeds and Northrup Speedomax 16-point recorder. The rod temperature was thus recorded at 3-sec intervals. The recorder was set on a range of 0 to 2.5 mv, corresponding to a temperature range of approximately 80 deg F.

Air flow was maintained by a Buffalo Forge Blower that was driven by a variable-speed motor. During runs at the higher flow rates, the air passed through a rectangular exhaust section and flow rate was determined by traverses with a Hastings precision air meter. The flow rate was determined at the lower flow rates by forcing the air through a 2.5-in. nozzle and measuring velocity by a pitot-static primary element connected to a micromanometer.

To run a test, the blower speed was adjusted to the desired flow rate while the copper test rod was heated on a hot plate to about 250 F. The test rod was then substituted for one of the dummy rods. The recorder began charting the temperature-time history of the rod as soon as the thermocouple output fell within the recorded range. As the test rod cooled, the flow-rate data were taken, the air-stream temperature was measured with a mercury thermometer, the pressure in the test section above atmospheric was measured by means of a water manometer, and the barometer reading was recorded.

Evaluation of Data

The excess of rod temperature over air-stream temperature was read, point by point, and replotted as a function of time on two-cycle, semi-log co-ordinate paper and the most representative straight line was drawn, as shown in Fig. 3. The slope was then calculated from two widely separated points read from the straight line. The total heat-transfer coefficient was then calculated from the equation

$$\frac{\ln (T_2 - T_a) - \ln (T_1 - T_a)}{t_2 - t_1} = - \frac{h_t \pi DL}{W_c C_c} \quad \dots \dots \dots (2)$$

Correction for Radiation

The heat-transfer coefficient as calculated by the foregoing procedure includes a small radiation effect. The net flux of radiant energy from the surface of the test rod is given by the equation

$$q_r' = \delta \epsilon (T^4 - T_a^4) = \delta \epsilon (T - T_a)(T + T_a)(T^2 + T_a^2)$$

assuming that the surrounding dummy rods comprise a black body at air-stream temperature. Then

$$h_r = \frac{q_r'}{T - T_a} = \delta \epsilon (T + T_a)(T^2 + T_a^2) \approx 4 \delta \epsilon T_{avg}^2 \dots \dots \dots (3)$$

where T_{avg} is the average absolute temperature of the rod during a run.

The surface of the test rod changed by oxidation as it was exposed to the air and by cleaning between tests, but $\epsilon = 0.60$ was taken as a reasonable average value for calculating h_r . The measured heat-transfer coefficient was then corrected by the relation $h = h_t - h_r$. The size of this correction was from 1.5 per cent to 3.5 per cent of the total value.

For generality, the heat-transfer coefficients were plotted, as $Nu/Pr^{1/3}$ against flow converted to Re , on logarithm co-ordinate paper.

Estimate of Error

An attempt has been made to estimate the magnitude of errors that might appear in the final results due to unsuspected causes. First we observe that the final heat-transfer coefficient is given in terms of measured quantities by the formula

$$h = - \frac{W_c C_c}{\pi D L} \frac{\ln (T_2 - T_a) - \ln (T_1 - T_a)}{t_2 - t_1} - h_r \dots \dots \dots (4)$$

It was conservatively estimated that the odds were twenty to one that the error in these measured quantities fell within the following intervals:

W_c ± 0.01 lb

C_c ± 0.005 Btu/lb deg F

D ± 0.006 in.

L ± 0.010 in.

$$T_1 - T_a \pm 0.02 \text{ mv}$$

$$T_2 - T_a \pm 0.02 \text{ mv}$$

$$t_2 - t_1 \pm 5.0 \text{ sec}$$

$$h_r \pm 0.4 \text{ Btu/hr sq ft deg F}$$

Following the procedure described by Kline and McClintock (4), it was calculated for a typical run that the odds were twenty to one (95 per cent confidence limit) that the fractional error in the heat-transfer coefficient fell within the interval ± 7.5 per cent.

Discussion of Results

The published work of other experiments shows that the heat-transfer coefficient in a staggered tube bank increases from the first row to the fourth, reaching essentially its asymptotic value at the fourth row (5).

For this reason, the results obtained with the test rod in Row 3 were plotted separately, as $Nu/Pr^{1/3}$ versus Re , in Fig. 4. In the lower Reynolds number range these results are compared with the Colburn Equation (1) into which has been inserted the factor 0.93, recommended by Kays and Lo (5). In the higher range of Reynolds numbers, the results are compared with the correlation of Sheehan, et al. (2) who found the asymptotic coefficient to have been reached by the third row. The Sheehan correlation is given as

$$h = 0.185 (Re)^{0.8} \text{ Btu/hr sq ft deg F}$$

This equation becomes

$$Nu = 0.0331 (Re)^{0.8} (Pr)^{1/3}$$

assuming that Nusselt number varies with Prandtl number to the one-third power.

Heat-transfer coefficients measured in the fifth and seventh rows are plotted in Fig. 5 and are correlated by the equation

$$Nu = 0.126 (Re)^{0.692} (Pr)^{1/3} \dots \dots \dots (5)$$

Again, the results are compared with the correlation of Sheehan, et al. and with the Colburn equation. These values are seen to be slightly higher than would be predicted by either the Colburn equation or the Sheehan equation. This tendency appears reasonable, however, since a smooth interpolation between the two curves must fall above the extrapolation of either.

The third-row results are not significantly different from the fifth-and seventh-row results. This is in agreement with the findings of Sheehan, et al., but not with the data of Kays and Lo.

VARIATION OF LOCAL HEAT-TRANSFER COEFFICIENTS

Basis of the Test

Variations in heat transfer around the circumference of a rod in crossflow were determined from mass-transfer data using the mass transfer = heat transfer analogy. The mass transfer j -factor is defined to be

$$j_m = \frac{kp}{\rho_a v/M_a} \left(\frac{\mu}{\rho_a k_d} \right)^{2/3} \dots \dots \dots \quad (6)$$

and is shown by Chilton and Colburn (5) to be equal under the proper conditions to the heat-transfer j -factor,

$$j_h = \frac{h}{c_p \rho_a v} \left(\frac{c_p \mu}{k_a} \right)^{2/3} \dots \dots \dots \quad (7)$$

The conditions under which this equality holds are closely approximated in the sublimation of naphthalene into an air stream at room temperature.

Description of Apparatus and Test Procedure

The same basic rod assembly and the same flow equipment were used in these tests as were used for the transient measurements of average heat-transfer coefficients, with the exception that a naphthalene rod replaced the heated copper rod.

The test rods were cast from sublimed flake naphthalene in a split brass mold of inside diameter 1.004 in. After removal from the mold, the rod was cut to the correct length and the regions next to the ends were wrapped with Scotch cellulose tape.

When the desired flow rate was obtained by adjusting the blower speed, a plexiglass rod was removed and replaced by a naphthalene rod. The rod was oriented with respect to the direction of flow by a mark that had previously been made on the end of the rod. The test was run for a sufficient length of time, from 3/4 to 2 hr, to remove from 0.01 in. to 0.02 in. from the surface of the rod. Temperature, pressure, and flow-rate measurements were taken several times during this interval. At the end of the test, the rod was removed and the end tape stripped off. A paper disk, marked in 10-increments, was glued onto one end with the zero mark pointing toward the oncoming air stream. The depth of surface removal was measured, with reference to the unexposed surface at the ends, at 10-deg intervals. These measurements were made by use of a comparator which projected an enlarged view of the rod on a screen. These measurements were made at the center cross section but were checked by measurements near the end. There was no significant variation between measurements at the two points.

Evaluation of Data

The local mass-transfer coefficients were calculated from the equation

$$K = \frac{y \rho_n}{p^0 M_n} \dots \dots \dots \quad (8)$$

The average coefficients were calculated in the same way using the average depth of naphthalene removal as computed by a planimeter integration of the local values. The corresponding j -factors were then found from the defining equation, using experimental values for flow rate, and air and naphthalene properties estimated from temperature and pressure data. For comparison with tests performed by other workers, the dimensionless variable $Nu/Pr^{1/3}$ was calculated from the relation

$$Nu/Pr^{1/3} = j_h Re$$

taking $j_h = j_m$. Heat-transfer coefficients also may be calculated from j_h by means of the defining equation. The values for the molecular diffusion coefficient were computed from the formula given by Sherwood and Pigford (6). The vapor pressures were calculated from the correlation given in "International Critical Tables" (7).

Discussion of Results

Average heat-transfer coefficients as measured by the mass-transfer technique are plotted in dimensionless form in Fig. 6 and compared with those obtained by transient tests. It is seen that the mass-transfer results are subject to more scatter than the transient results and average about 20 per cent higher. Comparison is also made with the Colburn equation and with the results of Winding and Cheney (8). The Winding and Cheney experiments also made use of the naphthalene mass-transfer technique but were performed on a bank of tubes 1.5 in. diam whose center-to-center spacing within a row was 2.25 in., with rows 3.00 in. apart. Winding and Cheney reported the correlation

$$Nu = 0.55 (Re)^{0.55}$$

which becomes

$$Nu = 0.622 (Re)^{0.55} (Pr)^{1/3}$$

assuming $Pr = 0.70$. The results reported here lie also above both of these correlations. There are several factors that the authors believe tend to make it more difficult to obtain accurate information by the mass-transfer technique. These are as follows:

1 A slight darkening of the naphthalene during the casting process indicates the possibility of chemical change that might influence the physical properties.

2 Although the rods were smooth immediately after casting, varying degrees of surface roughness developed during sublimation.

3 The vapor pressure of naphthalene changes rapidly with temperature. Data on vapor pressure in the range of room temperatures, and below, are meager.

4 Some of the rods tended to be porous or flaky after casting. Such rods, in general, were rejected, but detection of flaws was not always possible.

In spite of the errors in absolute values that appeared to creep into these experiments, the mass-transfer technique is nevertheless believed by the authors to be one of the better methods of detecting normalized variations in heat-transfer coefficients. Plots

of local heat-transfer coefficients for row 3 are shown in Figs. 7 and 8. Similar plots for rows 5 and 7 are shown in Figs. 9 and 10. The maximum deviations from the average coefficients are given in Table 1.

Table 1 Maximum Deviations from Average Coefficients

Row	Re	Max. Deviation from Ave. h (Per Cent)	
3	36000 - 43800	+79.5	-52.2
3	73700	+67.0	-47.3
5 and 7	36000 - 43800	+64.4	-54.5
5 and 7	73700	+57.8	-39.2

Point-to-point variations are somewhat greater than those reported by Winding and Cheney, but are in qualitative agreement. The results are not, however, in agreement with the findings of Dwyer, Sheehan, and Weisman (2). Dwyer, et al. measured local coefficients from staggered tubes to water at a temperature of 360 F using the same basic equipment as is described in (2). Maximum deviations from the average coefficient were reported to be +9 per cent and -6.1 per cent Re = 27,600, and +6 per cent and -1.4 per cent at Re = 74,200. At the same time, the sharp variation that the authors found, between 80 and 140 F from the forward stagnation point, were not reported by Dwyer, et al.

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CAPTIONS FOR ILLUSTRATIONS

Fig. 1 Basic model for heat-transfer tests

Fig. 2 Drawing of thermal capacitor for transient tests

Fig. 3 Temperature-time history of test rod

Fig. 4 Transient test results for third row

Fig. 5 Transient test results for fifth and seventh rows

Fig. 6 Average heat transfer measured by mass-transfer method

Fig. 7 Local heat-transfer coefficients for third row for $Re = 36,200 - 43,000$

Fig. 8 Local heat-transfer coefficients for third row for $Re = 73,700$

Fig. 9 Local heat-transfer coefficients for fifth and seventh rows for $Re = 36,200 - 43,000$

Fig. 10 Local heat-transfer coefficients for fifth and seventh rows for $Re = 73,700$

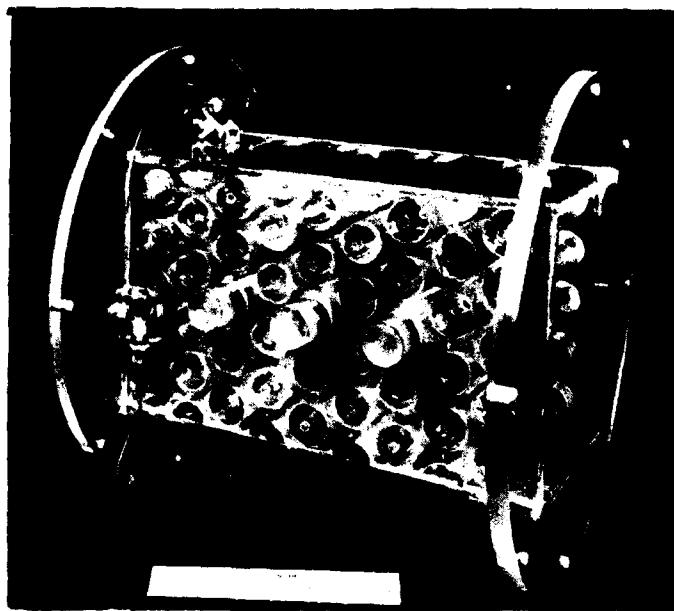


Fig.1

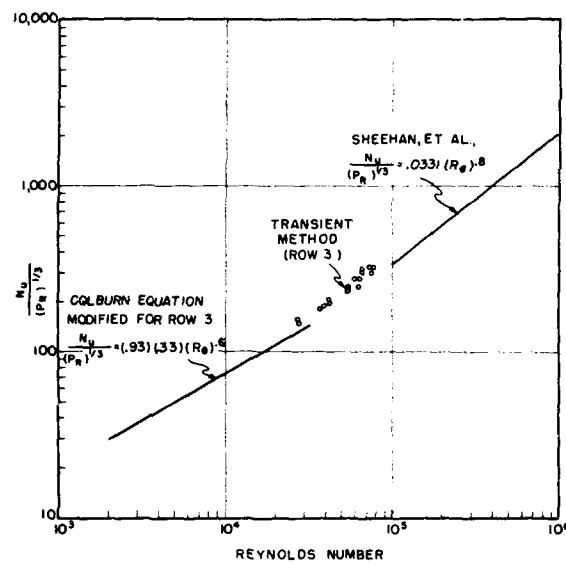


Fig.4

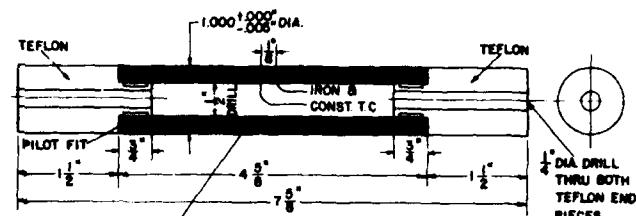


Fig.2

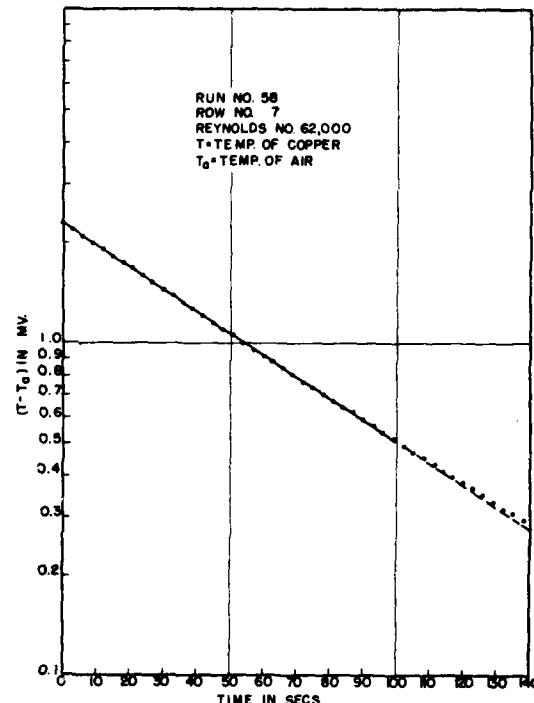


Fig.3

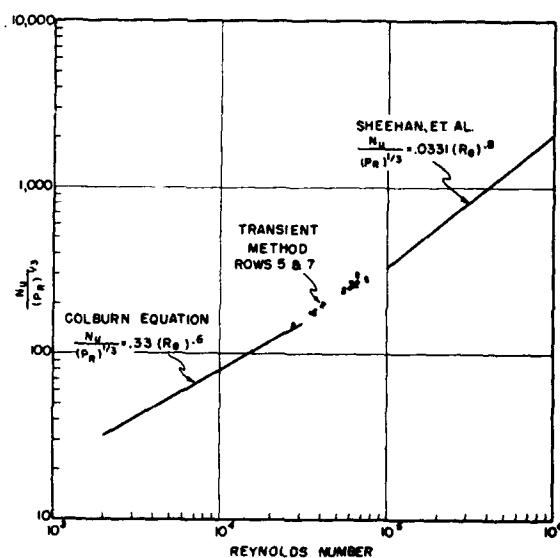
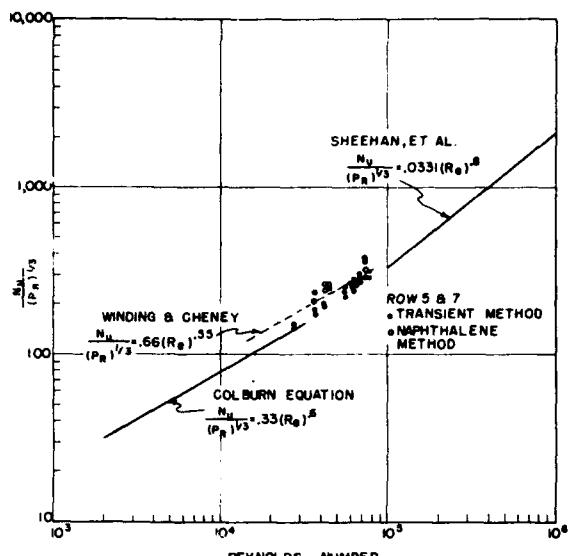


Fig.5



REYNOLDS NUMBER

Fig. 6

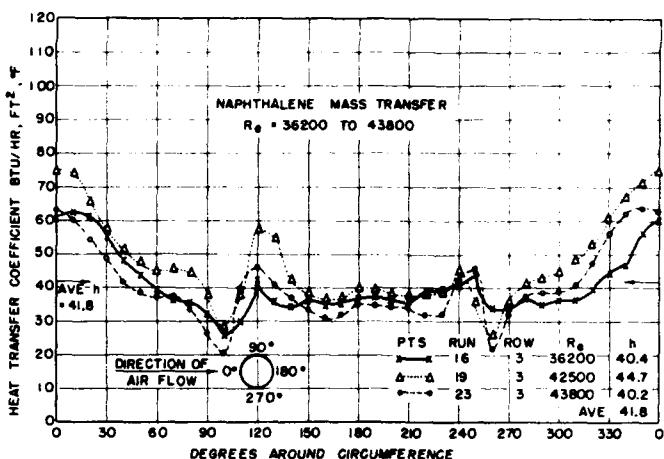


Fig. 7

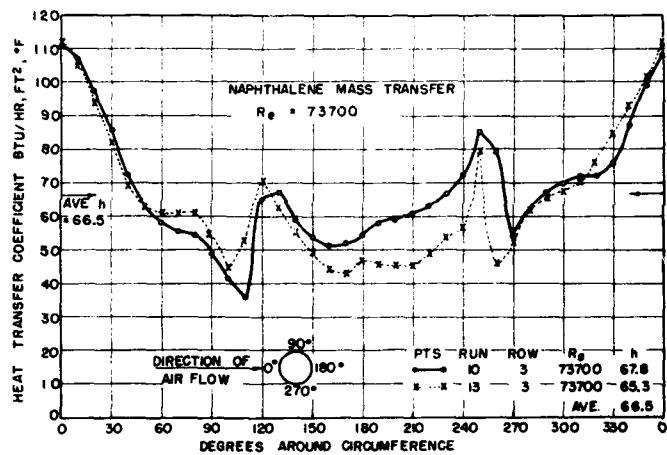


Fig. 8

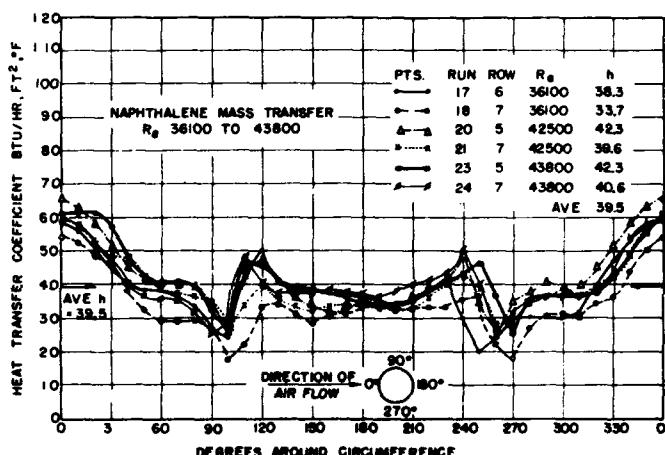


Fig. 9

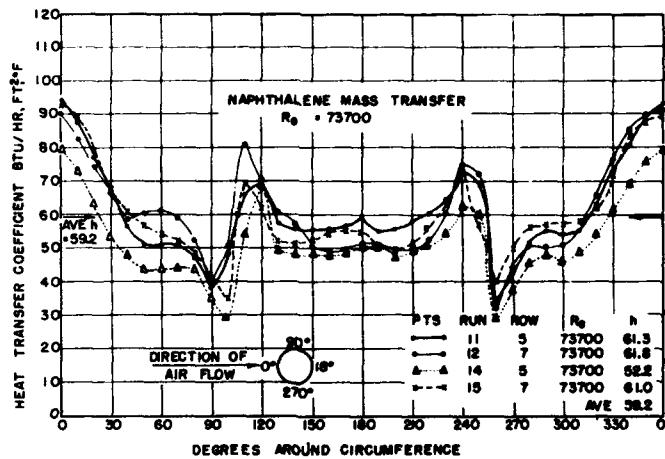


Fig. 10